

ENERGETIC PARTICLE OBSERVATIONS AND PROPAGATION IN THE THREE-DIMENSIONAL HELIOSPHERE DURING THE 2006 DECEMBER EVENTS

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ABSTRACT

We report observations of solar energetic particles obtained by the HI-SCALE and COSPIN/LET instruments onboard *Ulysses* during the period of isolated but intense solar activity in 2006 December, in the declining phase of the solar activity cycle. We present measurements of particle intensities and also discuss observations of particle anisotropies and composition in selected energy ranges. Active Region 10930 produced a series of major solar flares with the strongest one (X9.0) recorded on December 5 after it rotated into view on the solar east limb. Located over the South Pole of the Sun, at $>72^\circ$ S heliographic latitude and 2.8 AU radial distance, *Ulysses* provided unique measurements for assessing the nature of particle propagation to high latitudes under near-minimum solar activity conditions, in a relatively undisturbed heliosphere. The observations seem to exclude the possibility that magnetic field lines originating at low latitudes reached *Ulysses*, suggesting either that the energetic particles observed as large solar energetic particle (SEP) events over the South Pole of the Sun in 2006 December were released when propagating coronal waves reached high-latitude field lines connected to *Ulysses*, or underwent perpendicular diffusion. We also discuss comparisons with energetic particle data acquired by the *STEREO* and *Advanced Composition Explorer* in the ecliptic plane near 1 AU during this period.

Key words: Sun: coronal mass ejections (CMEs) – Sun: flares – Sun: magnetic fields – Sun: particle emission – solar wind

1. INTRODUCTION

Launched in 1990 October, the joint ESA/NASA *Ulysses* mission has explored the previously uncharted third dimension of our solar system. During its operational lifetime of almost 19 years, *Ulysses* completed three orbits carrying it over both poles of the Sun.

Although the Sun was again close to its activity minimum during the recently completed third polar orbit of *Ulysses*, solar activity has been more prevalent during the declining phase of Solar Cycle 23 (McKibben et al. 2005; Malandraki et al. 2007, 2008) than was the case in the declining phase of the 22nd solar cycle, when the first polar passes occurred (1994/1995) (e.g., Lario & Pick 2008). In 2006 December, an unexpected rise of solar activity occurred. Active Region 10930 near the Sun's equator began producing X-class flares almost as soon as it rotated onto the visible hemisphere of the Sun on December 5 (see Table 1). The *Ulysses* spacecraft was then luckily over the South Pole of the Sun, at $>72^\circ$ southern heliographic latitude and a heliocentric distance of ~ 2.8 AU. This provides a unique opportunity in the history of the *Ulysses* mission to study a large solar energetic particle (SEP) event at high heliolatitudes ($>70^\circ$ S) near solar minimum, with a relatively quiet and stable interplanetary structure in the heliosphere. In this work, we present in detail energetic particle observations (77 keV to ~ 20 MeV ions and 35–315 keV electrons) obtained during

this unique event by *Ulysses* and discuss their implications for particle propagation to high solar latitudes (see Heber et al. 2008 for a discussion of higher energy particle observations by *Ulysses* during this period). The observed events are also compared with high-latitude measurements obtained previously by *Ulysses* close to solar maximum. Furthermore, comparisons with data acquired by the *STEREO* and *Advanced Composition Explorer* (ACE) spacecraft near the ecliptic plane are discussed.

2. INSTRUMENTATION

In this paper, we use energetic particle data from the Cosmic Ray and Solar Particle Investigation (COSPIN)/Low Energy Telescope (LET) instrument (Simpson et al. 1992) and the Heliospheric Instrument for Spectra, Composition, and Anisotropy at Low Energies (HI-SCALE) instrument (Lanzerotti et al. 1992) onboard *Ulysses*. Magnetic field observations from the *Ulysses* magnetometer (VHM-FGM; Balogh et al. 1992) and solar wind measurements from the *Ulysses* Solar Wind Plasma experiment (SWOOPS; Bame et al. 1992) are also used. The COSPIN/LET instrument records, the fluxes, and the composition of solar energetic particles and low-energy cosmic ray nuclei from hydrogen up to iron over a range of energies from ~ 1 MeV/n to ≥ 50 MeV/n. Ion data from the LEMS120 telescope (Low Energy Magnetic Spectrometer) and differential intensities of 35–315 keV magnetically deflected electrons (DE) measured by the WART B detector head of the HI-SCALE experiment

Table 1
Significant Solar Events (M3 or Greater) Reported in 2006 December

| Flare | | | | CME ^a | | | |
|--------|-------------|------------------------|---------------------|------------------|-----------------------|-----------|-------------------------------|
| Date | X-Ray Onset | Flare Class | H α Location | NOAA AR | Time ^d | CME Width | V ^e _{CME} |
| 5 Dec | 339/1018 | X9.0/2N ^b | S07 E79 | 10930 | No LASCO observations | | |
| 6 Dec | 340/0802 | M6.0/SF | S07 E66 | 10930 | No LASCO observations | | |
| 6 Dec | 340/1829 | X6.5/3B ^{b,c} | S06 E63 | 10930 | 340/2012 | Halo | ... |
| 6 Dec | 340/2014 | M3.5 | S06 E58 | 10930 | ... | ... | ... |
| 13 Dec | 347/0214 | X3.4/4B ^b | S06 W24 | 10930 | 347/0254 | Halo | 1774 |
| 14 Dec | 348/2107 | X1.5/2B ^b | S06 W44 | 10930 | 348/2230 | Halo | 1042 |

Notes.

^a CME classification and parameters extracted from the SOHO/LASCO CME catalog at <http://cdaw.gsfc.nasa.gov/>.

^b Flare associated with intense metric type II radio burst (as reported in the SEC Preliminary Report and Forecast of Solar Geophysical Data published online at <http://www.swpc.noaa.gov/weekly/index.html> by the NOAA/SED and the AFWA).

^c Moreton wave observed to flow out of flare (<http://spaceweather.com/index.html>).

^d First appearance in the C2 coronagraph (>1.5 solar radii).

^e Plane of sky projected CME speed in km s^{-1} .

are also utilized. The WART B detector head has a geometrical factor of $\sim 0.05 \text{ cm}^2 \text{ sr}$. We also use electron intensities and their angular distributions in the energy range 178–290 keV detected by the sunward looking telescope LEFS60 (Low-Energy Foil Spectrometer) of the HI-SCALE experiment, which has a larger geometrical factor ($\sim 0.48 \text{ cm}^2 \text{ sr}$). Energetic particle data measured in the ecliptic plane near 1 AU were obtained from the Low Energy Telescope (LET; Mewaldt et al. 2008) of the in situ measurements of particles and CME transients investigation (IMPACT; Luhmann et al. 2008) onboard the *STEREO* spacecraft and the Electron, Proton, Alpha Monitor (EPAM) instrument onboard the *ACE* spacecraft (Gold et al. 1998). EPAM was adapted from the flight-spare unit of the *Ulysses*/HI-SCALE instrument.

3 OBSERVATIONS AND DATA ANALYSIS

3.1. Solar Activity

Table 1 contains a list of the major solar events and their characteristics for 2006 December. M3 or greater class flares and associated coronal mass ejections (CMEs) are listed. The solar flares are as reported in the solar geophysical data (<http://sgd.ngdc.noaa.gov/sgd/jsp/solarindex.jsp>) whereas, when available, CME identification and parameters were obtained from the *Solar and Heliospheric Observatory*/Large Angle and Spectrometric Coronagraph (*SOHO*/LASCO) CME catalog compiled by S. Yashiro and G. Michalek (available at <http://cdaw.gsfc.nasa.gov/>). After it rotated into view on the east limb, Active Region 10930 began producing a series of X- and M-class flares. The four X-class flares during this period of isolated but intense solar activity are highlighted using the bold-faced type in Table 1. The strongest one was an X9.0 solar flare recorded on December 5 at S07 E79 as viewed from the Earth. On December 6, region 10930 produced an X6.5 flare, and as it rotated across the solar disk, two more X-class flares were observed on December 13 and 14, both in the western hemisphere of the Sun and both associated with fast halo CMEs. All X-ray flares of this period were associated with particularly intense metric type II radio bursts, indicative of propagating coronal shock waves at the Sun (e.g., Vainio & Khan 2004; Mann 2006). Furthermore, a rare Moreton wave—aka “solar tsunami” was observed to flow out of the X6.5 flare (<http://spaceweather.com/index.html>).

3.2. High-latitude Observations

Figure 1 shows the position of *Ulysses*, then at a heliocentric distance of ~ 2.8 AU and at $>72^\circ$ southern heliographic latitude, with respect to the fixed Sun–Earth line, projected onto the solar equatorial plane as viewed from the north (top) and on a plane perpendicular to the solar equator as viewed from the Earth toward the Sun (bottom) on DOY 339 (December 5) (left) and DOY 347 (December 13) (right). The ideal Archimedes spiral magnetic field lines connecting *Ulysses* to the Sun are also shown, calculated using the measured solar wind speed at *Ulysses* on the two days. The negative values in red correspond to locations east of the central meridian. On December 5, there was an angular separation of 70° in longitude between the nominal *Ulysses* magnetic footpoint and the X9.0 flare location. The great circle angular separation between the spacecraft footpoint and the flare was $\sim 77^\circ$. This separation was $\sim 135^\circ$ for the Earth. Subsequently, as the Sun rotated, *Ulysses* became more poorly connected, while the Earth became better connected to the flare sites.

In the top panel of Figure 2, an overview of the spin-averaged energetic ion intensities as measured by the *Ulysses*/HI-SCALE LEMS120 telescope in the energy range 77–1123 keV and the *Ulysses*/COSPIN/LET telescope in the energy range 1.8–19 MeV in 2006 December is presented. The second panel presents the integral rate of higher energy (>50 MeV) ions as measured by COSPIN/LET. The vertical arrows in this panel indicate the occurrence of the flares in Table 1. Longitude information is given for the four X-class flares observed. Magnetically deflected near-relativistic electrons (DE) as measured by the WART B detector head of the HI-SCALE experiment for the same period are shown in the third panel. The panels below present solar wind velocity and interplanetary magnetic field (IMF) magnitude, meridional angle, and azimuth angle in the *Ulysses* Radial-Tangential-Normal (RTN) coordinate system (Forsyth et al. 1995). The radial solar distance and the heliographic latitude of the spacecraft are shown at the top of Figure 2. The HI-SCALE ion channels may be contaminated at the beginning of large SEP events when many electrons arrive promptly, well before the slower ions can reach the spacecraft (e.g., Lario et al. 2004). By comparing electron intensities with low-energy ion intensities and COSPIN/LET intensities with HI-SCALE/LEMS120 intensities in 2006 December, we conclude that the <1 MeV ion channels of the LEMS120 were contaminated in

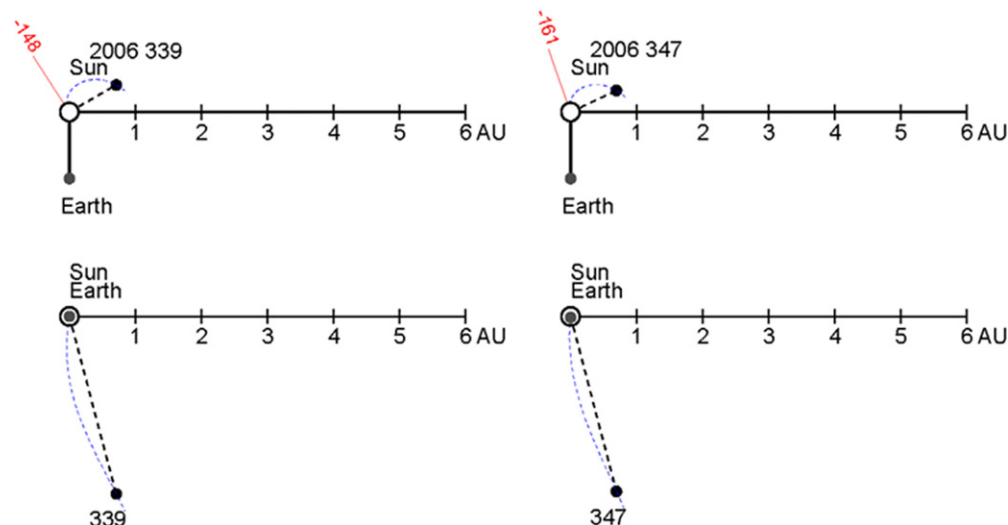


Figure 1. Position of *Ulysses* with respect to the fixed Sun–Earth line on December 5 (DOY 339) and 13 (DOY 347); see the text.

the rising phase of the SEP event by electrons bypassing the magnetic deflection system. We have indicated this period by dotted traces in Figure 2. The solid vertical lines in Figure 2 indicate the time of passage of three forward (F) shocks during this period. The shocks are obvious from the abrupt increases in the solar wind speed and magnetic field magnitude. No associated driver ejecta signatures were detected during this period (Ebert et al. 2009; Liu et al. 2008). This constitutes a unique observation by *Ulysses* at high latitudes.

As is evident from Figure 2, major SEP events were observed by *Ulysses* in response to the rise of solar activity in 2006 December. These events were observed when *Ulysses* was immersed in the high speed solar wind flow emanating from the southern polar coronal hole (McComas et al. 2008). As discussed below, the shocks observed are most likely related to Active Region 10930 and the associated X-class flares. The shocks arrive at *Ulysses* on DOY 344 (December 10), 345 (December 11), and 351 (December 17) so the delays with respect to the X-ray flare onsets are all about five days, consistently implying shock speeds of the order of 1000 km s^{-1} . However, what is striking is that shocks associated with low-latitude events are able to reach *Ulysses* at the South Pole of the Sun. The 2006 December 13 CME, evolved into a Magnetic Cloud driving a strong interplanetary shock, observed by near-Earth spacecraft (*STEREO*, *ACE*; Liu et al. 2008); see Section 3.3. Propagation of the solar wind data outward from 1 AU using an magnetohydrodynamic model showed *Ulysses* observed the same shock on December 17 as *ACE/STEREO*. This CME-driven shock was, thus, observed at both the Earth and *Ulysses* when they are separated by 74° in latitude and 117° in longitude, the largest shock extent ever detected in the space era (Liu et al. 2008).

Two separate enhancements are clearly distinguished in the $>50 \text{ MeV}$ ions and near-relativistic electron profiles in response to the X9.0 and X6.5 flares (Figure 2), with the second enhancement being more pronounced, possibly due to the very strong Moreton wave observed to flow out of the X6.5 flare leading to a more efficient acceleration of particles at these energies. For the later flares of this period, increases are only barely observed over the background level for the $>50 \text{ MeV}$ ion intensity and superposed on the decaying near-relativistic electron intensities. This is most likely due to the poorer

magnetic connection of *Ulysses* to the flares during this period. At quiet times, the COSPIN/LET 8–19 MeV proton channel mainly responds to high-energy particles (galactic cosmic rays), but when the level of solar activity increases, it responds primarily to solar particles in the nominal energy range. One large gradual SEP event is observed in this energy channel. The onset and decay profiles of the event for 8–19 MeV protons were relatively smooth (Figure 2). The event has a “clean” onset, occurring in a period nearly devoid of solar wind structures and with relatively low pre-event intensities. The onset time at *Ulysses* is defined as the time when the intensities exceed by more than 2σ the background intensity, requiring that they continue to rise from then. Using 10 minute averaged data, we have found that the 8–19 MeV proton intensities are observed to start increasing at $23:40 \text{ UT} \pm 0.166 \text{ hr}$ i.e., $\sim 13 \text{ hr}$ after the X9.0 flare. Using the solar wind velocity of 780 km s^{-1} measured by the *Ulysses*/SWOOPS experiment at the time of the event the Parker spiral magnetic field line connecting *Ulysses* to the Sun is computed to be $\sim 2.88 \text{ AU}$ long. The earliest expected onset time for protons propagating from the Sun along the field using the velocity of the highest energy ions contributing to the 8–19 MeV channel is calculated to be $\sim 1.98 \text{ hr}$ after the onset of the X9.0 flare. Comparison with the observations shows that the onset at *Ulysses* is considerably delayed. A slower rate of rise is observed after the occurrence of the X6.5 flare in the 8–19 MeV proton channel. No additional increase in the proton profiles in this channel was observed in response to the December 13 and 14 flares, possibly because it was masked by the already high pre-existing intensities (also the case for the near-relativistic electrons) and/or due to the poorer magnetic connection of *Ulysses* during this period. However, increases were observed in the lower energy profiles, with the lowest energy particles observed by HI-SCALE peaking at the time of passage of the shocks on DOY 345 and 351, suggesting a mixture of particles due to solar events and locally accelerated particles by the traveling interplanetary shocks.

Figure 3 focuses on the onset of the SEP event and shows differential proton intensities in the energy range 1.8–19 MeV as measured by the COSPIN/LET instrument for the 2006 December 5–9 period. A velocity dispersion effect, with the higher energy particles starting to be detected earlier than the lower energy particles, is evident at the onset of the event

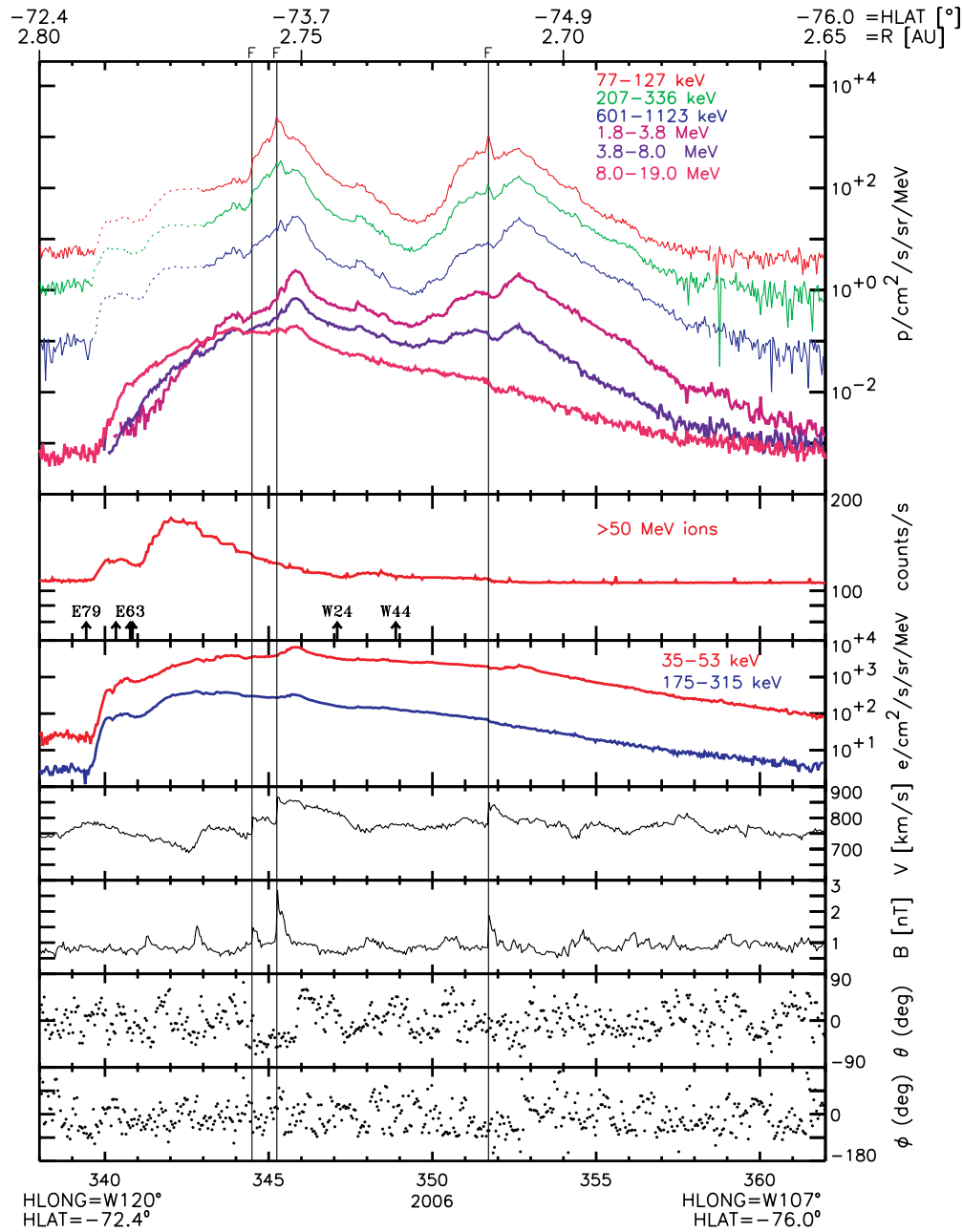


Figure 2. Overview of energetic particle observations as measured by the COSPIN/LET and HI-SCALE instruments onboard *Ulysses*, solar wind and magnetic field magnitude and directions in 2006 December. Solid vertical lines mark the arrival of interplanetary shock disturbances at *Ulysses*. Dotted traces in the HI-SCALE/LEMS120 ion time intensity profiles indicate time intervals with possible electron contamination.

following the X9.0 flare. This is a noteworthy feature, not usually observed at COSPIN/LET energies up to 19 MeV at the location of *Ulysses* (~ 3 AU). It is reminiscent of particle events observed near the Earth. This is probably due to the fact that this is an isolated SEP event that occurred during a period of relatively quiet and stable conditions in the heliosphere. However, the observed time difference between the onsets at different energies by *Ulysses* was ~ 1 day, which is not consistent with the expected time delays for direct propagation along a Parker spiral, suggesting that the particles have undergone considerable diffusion.

3.2.1. Composition Analysis

Figure 4 shows heavy ion differential energy spectra for C, O, and Fe ions in the energy range ~ 4 –30 MeV/n as measured by

the COSPIN/LET instrument, averaged over the period DOY 340–350 of 2006. Errors bars are presented for all points for O and C, whereas only one representative error bar is shown for Fe. This period includes the two flare-related increases observed by the LET. No measurable heavy-ion fluxes were recorded by the LET beyond DOY 350. Also shown in Figure 4 are power-law fits to the data. The statistical errors have been used in the fit. The spectra for C and O show very similar spectral slopes over the measured energy range ($\gamma = -1.4 \pm 0.1$), leading to an average C/O ratio of 0.41, typical of large SEP events. The Fe spectrum, which has been offset by a factor of 0.5 for clarity, appears to have a slightly steeper slope ($\gamma = -1.6 \pm 0.2$), although the scatter in the individual points is large. Taking a simple event average, we find an Fe/O ratio of ~ 0.3 , indicating that the event is somewhat iron-rich.

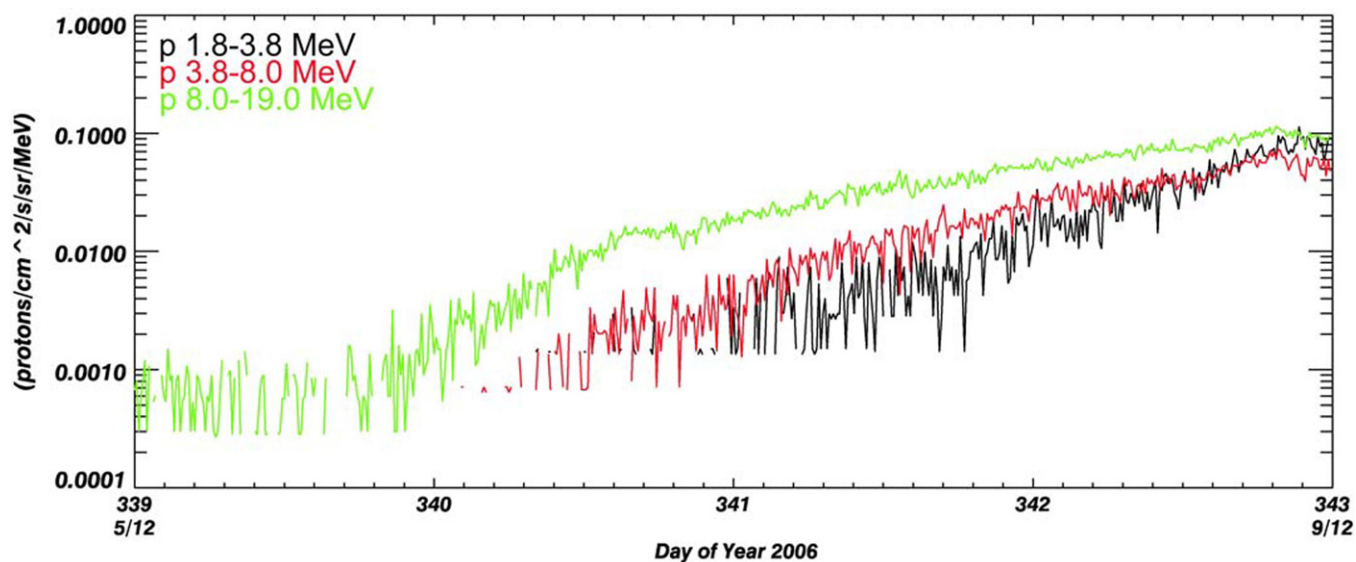


Figure 3. Zooming into the onset of the SEP event reveals a clear velocity dispersion effect is observed.

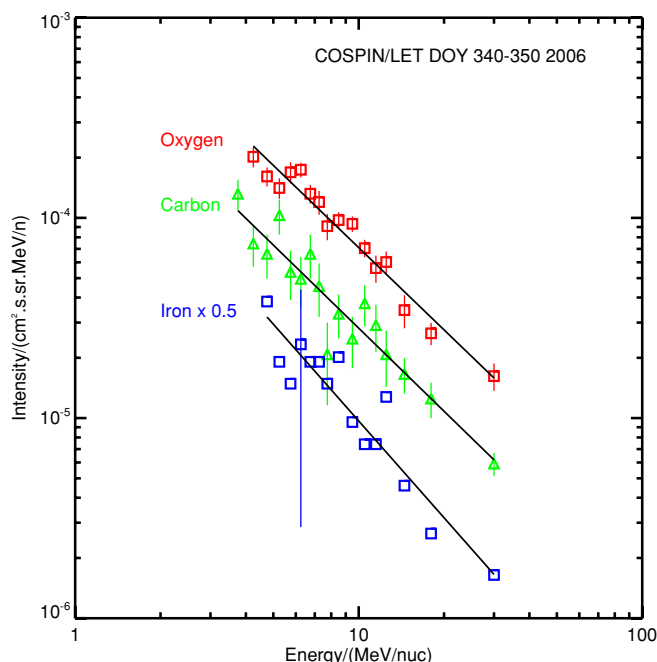


Figure 4. Heavy ion differential energy spectra for C, O, and Fe ions in the energy range ~ 4 –30 MeV as measured by the COSPIN/LET instrument, averaged over the period 340–350, 2006. Power-law fits to the data are also shown.

3.3. In-ecliptic 1 AU versus High-latitude Observations

Stereos A and B were still near Earth and not well separated in 2006 December, so their observations were essentially identical. In Figure 5, differential proton intensities in the energy range 1.8–15 MeV as measured by the LET experiment onboard the *STEREO B* spacecraft are shown for the period DOY 339–359, 2006. The spiky intensity increases observed on DOY 346 are associated with a radiation belt pass. The vertical arrows indicate the occurrence of the flares during this period (Table 1). The solid vertical lines correspond to the time of passage of three Forward shocks during this period identified by an abrupt increase in density, temperature, flow speed, magnetic field strength, and total pressure (not shown); see also (Liu

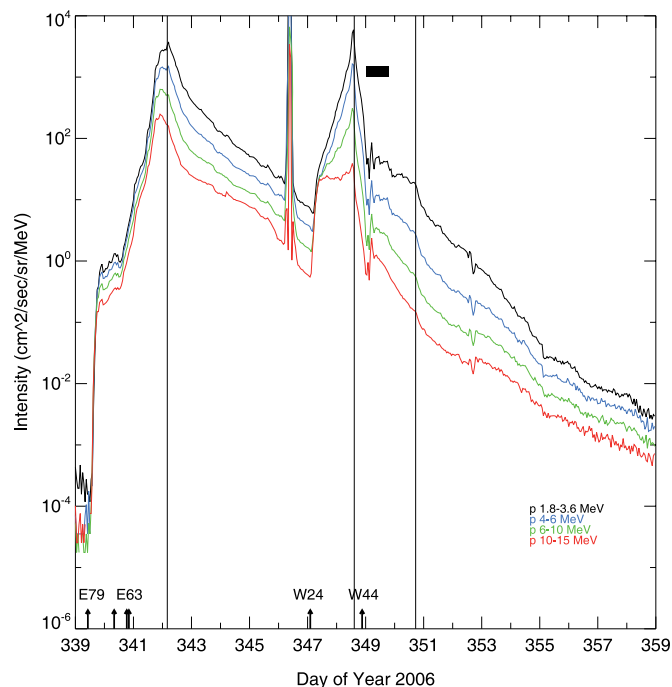


Figure 5. Differential proton intensities in the energy range 1.8–15 MeV as measured by the LET experiment onboard *STEREO B* spacecraft for the period DOY 339–359, 2006. Solid vertical lines denote the passage of three forward shocks during this period. The black horizontal bar indicates the passage of a magnetic cloud over *STEREO B*.

et al., 2008). The black horizontal bar indicates the passage of a magnetic cloud as identified by Liu et al. (2008), based on bi-directional streaming electrons (BDEs), rotation of the field and low field variance. No plasma parameters were available from *STEREO* during this period. Complementary plasma parameters from *ACE* reveal the passage of an interplanetary coronal mass ejection (ICME), with the magnetic cloud indicated by the *STEREO* BDEs being about the first half of the ICME interval (Liu et al. 2008).

Figure 6 shows hourly averages of 175–315 keV magnetically deflected electron intensities as measured by the WART B

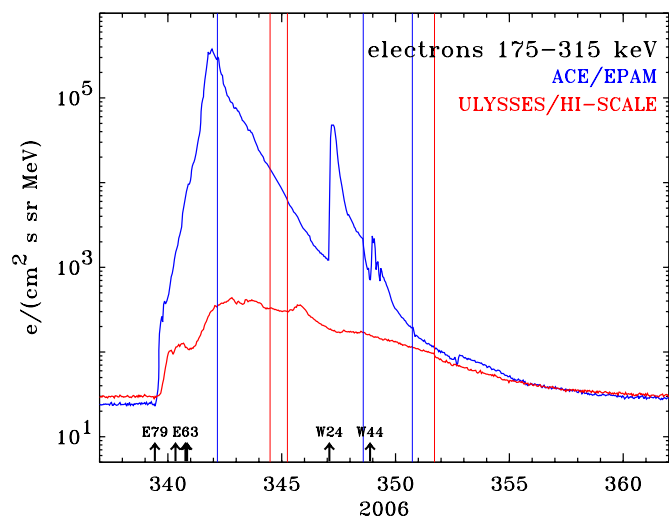


Figure 6. Comparison of near-relativistic electron intensities at high latitudes with those in the ecliptic plane near 1 AU by the two identical instruments *ULYSSES*/HI-SCALE and *ACE*/EPAM, respectively.

detector head of the HI-SCALE experiment onboard *Ulysses* (red trace) and by the EPAM experiment, a reconfigured version of HI-SCALE onboard *ACE* at 1 AU (blue trace), during the 2006 December period. The intensities at the two locations achieved near equality only very late in the decay phase of the particle events, indicating the presence of the “reservoir effect” (Roelof et al. 1992), but only during that time interval. This effect was observed more prominently by *Ulysses* at high latitudes in the very disturbed interplanetary environment characteristic of solar maximum (e.g., McKibben et al. 2003).

Figure 7 presents 178–290 keV electron intensities and their angular distributions as measured by the sunward looking telescope LEFS60 of the *Ulysses*/HI-SCALE and *ACE*/EPAM experiments during the onset of the event following the X9.0 flare on December 5. Pre-event background intensities have been subtracted to better visualize the onset of the event. Using 1 minute averaged data and defining the onset time of the event at *ACE* and *Ulysses*, as the time when the intensities get $>2\sigma$ above background and continue to rise from then on, the observed time delay between the arrival of the 178–290 electrons and the onset of the soft X-ray flare (vertical arrow in Figure 7) was 3.65 ± 0.016 hr for *ACE* and 9.55 ± 0.016 hr for *Ulysses*. Using the solar wind velocity of 320 km s^{-1} measured by the *ACE*/SWEPAM experiment (not shown) at the time of the event the Parker spiral

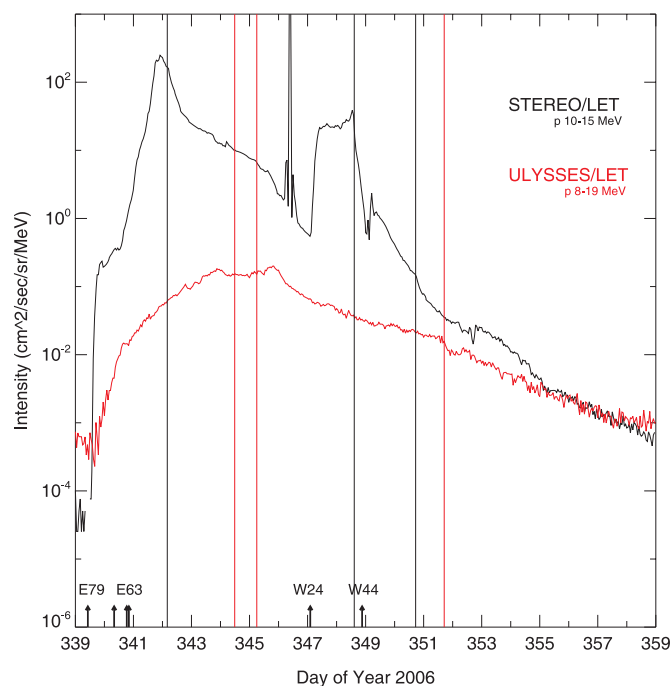


Figure 8. Hourly averages of proton intensities at similar energies as measured by the *Ulysses*/COSPIN/LET and *STEREO*/LET during the 2006 December period. Evidently, the rise time of the event at *STEREO* in response to the X9.0 flare is faster than at *Ulysses*.

magnetic field line connecting *ACE* to the Sun is computed to be ~ 1.23 AU long. The earliest expected onset time for directly arriving near-relativistic electrons (~ 250 keV) propagating from the Sun along the field would be 14 minutes after the onset of the X9.0 flare. This corresponds to a not well-connected event as viewed from the Earth. The expected time delay between the arrival of these particles at *Ulysses*, travelling along a ~ 2.88 AU long Parker spiral magnetic field line connecting *Ulysses* to the Sun, and the onset of the soft X-ray flare would be 33 minutes, showing this is a considerably delayed onset. Pitch-angle distributions at the onset of the event (insets at Figure 7) show a strong anisotropic flow away from the Sun at *ACE*, while at *Ulysses* near-isotropic electron angular distributions are observed after the onset of the event. The magnetic field in the fast solar wind is much more turbulent than in the slow solar wind, so propagation in the fast solar wind should be much more difficult (e.g., Sanderson 2004; Suess 2008) leading to

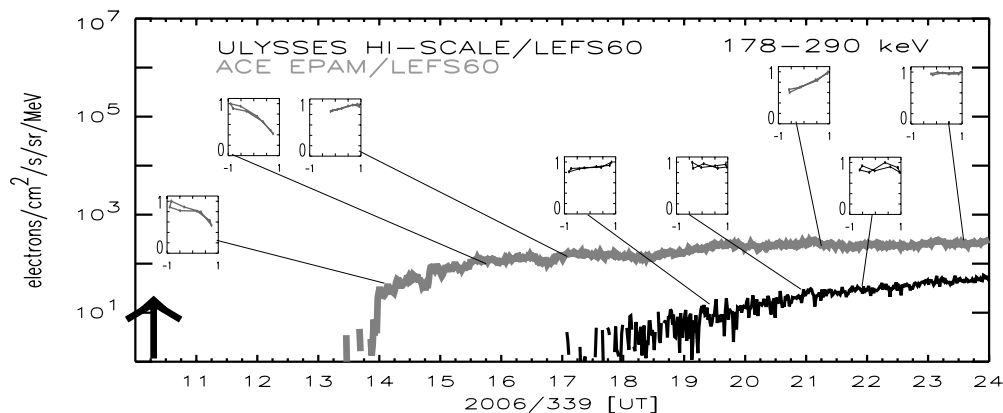


Figure 7. 178–290 keV electron intensities as measured by HI-SCALE/LEFS60 (black trace) and EPAM/LEFS60 (gray trace) at the onset of the event. The vertical arrow indicates the onset of the X9.0 flare on December 5. The insets show the pitch-angle distributions for the 8 sectors of the detector LEFS60 in both instruments.

significant scattering of the particles. Figure 8 shows hourly averages of proton intensities at similar energy intervals as measured by the COSPIN/LET and *STEREO*/LET experiments onboard *Ulysses* (red trace) and *STEREO B* (black trace) during the 2006 December period. The rise time of the event at *ACE* (Figure 6) and *STEREO* (Figure 8) in response to the X9.0 flare is faster than at *Ulysses* (although this corresponds to an eastern poorly connected event as viewed from the Earth). Thus, the onset of the SEP event at *Ulysses* suggests a more diffusive transport to high latitudes than to near-Earth spacecraft.

4. DISCUSSION

We report observations of unique large SEP events detected by *Ulysses*, during its third solar orbit, in 2006 December over the Sun's South Pole that occurred near solar minimum with a relatively quiet and stable interplanetary structure in the heliosphere. Throughout the first solar-minimum orbit of *Ulysses* only a very weak electron event observed at $\sim 73^\circ$ S (Pick et al. 1995) was the highest latitude SEP event observed (Lario & Pick 2008). The origin of the events in 2006 December was almost certainly the series of solar flares observed at low latitudes between December 5 and 14.

The correlation between the large SEP events at near-Earth spacecraft (*STEREO*, *ACE*) and *Ulysses* suggests an easy access of SEPs at both low and high latitudes. Delayed onsets were detected for both the electrons and ions by the HI-SCALE and COSPIN/LET instruments onboard *Ulysses*. In order to explain the observation of large SEP events at high heliographic latitudes by *Ulysses* during its solar maximum orbit, Smith et al. (2001) suggested that SEPs access high latitudes via the complex magnetic field topology existing during solar maximum, where field lines originating at low latitudes may reach the polar regions. The relatively simple structure of the heliosphere near solar minimum as well as the observation of the 2006 December events when *Ulysses* was immersed in the southern high-speed coronal hole solar wind flow seems to exclude the possibility that magnetic field lines originating at low latitudes reached *Ulysses*. Very intense metric type II radio bursts were associated with the X-ray flares of this period, which provide evidence for strong propagating coronal shock waves at the Sun. Moreover, a rare Moreton wave flowing out of the X6.5 flare was observed. Moreton and EIT (Extreme-Ultraviolet Imaging Telescope) waves have been often associated with SEP events (Cliver et al. 1995; Torsti et al. 1998, 1999; Vainio & Khan 2004; Mann 2006). The energetic particles observed as large SEP events over the South Pole of the Sun in 2006 December may therefore have been released when the propagating coronal waves reached high-latitude magnetic field lines connected to *Ulysses*. Calculations show that a coronal shock wave propagating away from the X9.0 flare at S07 would have to travel a distance of about 800,000 km across the solar disk to reach magnetic field lines at S73 connected to *Ulysses*. Assuming a speed of $\sim 1000 \text{ km s}^{-1}$ for the coronal shock wave this implies a time delay of ~ 13 minutes, which would lead to a somewhat late injection of particles into high-latitude field lines connecting to the spacecraft. However, this delay apparently corresponds to a small fraction of the observed onset delays for both the ions and electrons.

An alternative explanation of the access of energetic particles at high latitudes in 2006 December may be the possibility of particle diffusion perpendicular to the mean magnetic field, able to spread the particles in the latitudinal direction, as originally suggested to explain the *Ulysses* observations during the Bastille Day 2000 event at high southern latitudes during solar maximum

(Zhang et al. 2003). Dalla et al. (2003) who analyzed nine high-latitude events observed by *Ulysses* are in agreement with the suggestion by Zhang et al. (2003). Note that for the Bastille Day 2000 event, a transient structure complicated the interpretation of the anisotropies observed (Sanderson 2004, 2005). Efficient cross-field diffusion close to the observer can be excluded during the rising phase of the 2006 December events since the particle flow directions were along the field and there was no evidence for any net flow across the field lines (Figure 7). Observations in the 2006 December events suggest that the particles propagated to high latitudes traveling along the magnetic field lines and not by crossing them. The particles were scattered significantly as they propagated outward, which explains their relatively slow onset and their small anisotropy, but despite this, any net flow direction was still along the local magnetic field line direction. On the basis of the observations available, however, cross-field diffusion closer to the Sun cannot be definitely excluded. These features are reminiscent of the four large SEP events *Ulysses* observed in fast solar wind during its second northern polar pass near solar maximum (Sanderson 2004, 2005; Lario et al. 2004). However, the 2006 December series of events that occurred during a period with relatively quiet and stable interplanetary conditions in the heliosphere, constitute a unique set of observations not seen previously during the entire *Ulysses* mission.

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